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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : F23N 5/18, 1/02

A1

(11) International Publication Number: WO 91/06809

(43) International Publication Date: 16 May 1991 (16.05.91)

(21) International Application Number: PCT/US90/05692

(22) International Filing Date: 9 October 1990 (09.10.90)

(30) Priority data:
429,138 30 October 1989 (30.10.89) US

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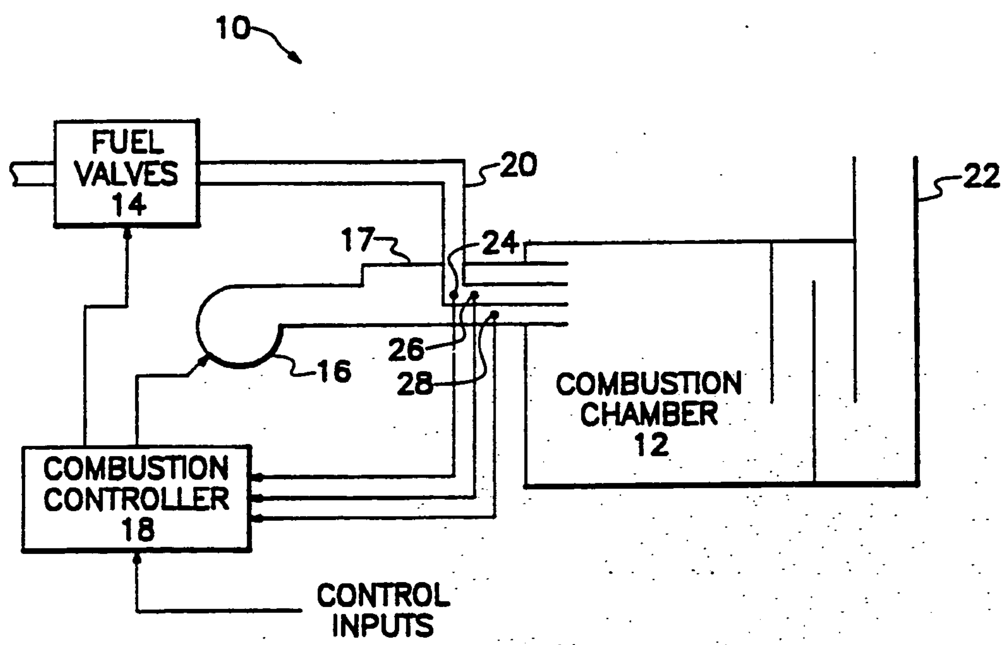
(81) Designated States: AT (European patent), AU, BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), GR (European patent), IT (European patent), LU (European patent), NL (European patent), SE (European patent).

**Published**
*With international search report.*

(54) Title: MICROBRIDGE-BASED COMBUSTION CONTROL




(57) Abstract

In a combustion system, fuel flow and fuel composition are sensed, and energy flow in the combustion system is determined based on the fuel flow and the fuel composition. Air flow of combustion air is also sensed. The fuel-to-air ratio in the combustion system is controlled as a function of the energy or oxygen demand flow determined and the air flow sensed.

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# MICROBRIDGE-BASED COMBUSTION CONTROL

## BACKGROUND OF THE INVENTION

### 1. Incorporation by Reference.

The following commonly assigned applications are co-pending with this application and are hereby incorporated by reference:

Serial No. 210,892, filed June 24, 1988 "MEASUREMENT OF THERMAL CONDUCTIVITY AND SPECIFIC HEAT"; Serial No. 211,014, filed June 24, 1988, entitled "MEASUREMENT OF FLUID DENSITY".

Serial No. 285,897, filed December 16, 1988 entitled "FLOWMETER FLUID COMPOSITION CORRECTION"; Serial No. 285,890, filed December 16, 1988 entitled "LAMINARIZED FLOWMETER".

### 2. Field of the Invention.

The present invention relates to controlling the combustion process for a heating system. More particularly, the present invention relates to controlling a fuel-to-air ratio of that combustion process.

### 3. Description of the Prior Art

There are many applications for industrial and commercial heating systems such as ovens, boilers and burners. These heating systems are generally controlled by some type of control system which operates fuel valves and air dampers to control the fuel-to-air ratio which enters the heating system. It is generally desirable to sense the fuel-to-air ratio to achieve a desired combustion quality and energy efficiency.

Conventional sensing of the fuel-to-air ratio has taken two forms. The first form includes sensing the concentration of carbon dioxide or

oxygen in flue gases. This method of sensing the proper fuel-to-air ratio is based on an intensive measurement of the flue gases. However, in practice, this method has encountered problems of reliability due to inaccuracy in the sensors which are exposed to the flue gases. Problems related to response time of the sensors have also been encountered. The system cannot sense the carbon dioxide and oxygen components of the flue gasses and compute the fuel-to-air ratio quickly enough for the fuel and air flow to be accurately adjusted.

The second form includes monitoring the flow rate of the fuel and air as it enters the burner. This method leads to a desirable feed-forward control system. However, until now, only flow rate sensors have been involved in this type of monitoring system. Therefore, the system has been unable to compensate for changes in air humidity or fuel composition.

## SUMMARY OF THE INVENTION

The present method is responsive to a need to control a fuel-to-air ratio in a combustion heating system based on fuel composition to achieve a desired combustion and energy efficiency. Fuel flow and air flow are sensed in the combustion system. Fuel composition is also sensed. Energy or oxygen demand flow to the combustion system is determined based on the fuel flow and the fuel composition. The fuel-to-air ratio is controlled as a function of the energy or oxygen demand flow determined and the air or oxygen supply flow sensed.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a heating system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 shows a block diagram of heating system 10. Heating system 10 is comprised of combustion chamber 12, fuel valves 14, air blower 16 and combustion controller 18. Fuel enters combustion chamber 12 through fuel conduit 20 where it is combined with air blown from air blower 16. The fuel and air mixture is ignited in combustion chamber 12 and resulting flue gases exit combustion chamber 12 through flue 22.

Combustion controller 18 controls the fuel-to-air mixture in combustion chamber 12 by opening and closing fuel valves 14 and by opening and closing air dampers in air conduit 17. Combustion controller 18 controls the fuel-to-air mixture based on control inputs entered by a heating system operator as well as sensor inputs received from sensors 24 and 26 in fuel conduit 20, and sensor 28 in air conduit 17.

Sensors 24, 26 and 28 are typically microbridge or microanemometer sensors which communicate with flowing fuel in fuel conduit 20 and flowing air in air conduit 17. This type of sensor is described in more detail in co-pending, related application serial no. 285,890, filed on December 16, 1988 and assigned to the common assignee of the present application.

Sensors 24 and 28 are directly exposed to the stream of fluid flowing past them in conduits 20 and 17, respectively. Sensors 24 and 28 are used to directly measure dynamic fluid flow characteristics of the respective fluids.

Microbridge sensor 26 enables other parameters of the fuel to be measured simultaneously with the dynamic flow. Sensor 26 can be used for the direct measurement of thermal conductivity, k, and specific heat, $c_p$, in accordance with a technique which allows the accurate determination of both properties. That technique contemplates generating an energy or temperature pulse in one or more heater elements disposed in and closely coupled to the fluid medium in conduit 20. Characteristic values of k and $c_p$ of the fluid in conduit 20 then cause corresponding changes in the time variable temperature response of the heater to the temperature pulse. Under relatively static fluid flow conditions this, in turn, induces corresponding changes in the time variable response of more temperature responsive sensors coupled to the heater principally via the fluid medium in conduit 20.

The thermal pulse need be only of sufficient duration that the heater achieve a substantially steady-state temperature for a short time. Such a system of determining thermal conductivity, k, and specific heat, $c_p$, is described in greater detail in co-pending applications serial no. 285,897, filed December 16, 1988 and serial no. 210,892, filed June 24, 1988 and assigned the same assignee as the present application.

It has also been found that once the specific heat and thermal conductivity of the fluid have been determined, they can be used to determine the density or specific gravity of the fluid. This technique is more specifically illustrated and described in patent application, serial no. 211,

014, also filed June 24, 1988, and assigned to the same assignee as in the present application. Of course, these parameters can be determined by other means if such are desirable in other applications.

Once k and $c_p$ are known, shift correction factors in the form of simple, constant factors for the fuel can be calculated. The shift correction factors have been found to equilibrate mass or volumetric flow measurements with sensor outputs. In other words, once k and $c_p$ of the fuel gas is known, its true volumetric, mass and energy flows can be determined via the corrections:

$$S^* = S(k/k_0)^m \, (c_p/c_{p0})^n \qquad \text{Eq. 1}$$

$$V^* = V(k/k_0)^p \, (c_p/c_{p0})^q \qquad \text{Eq. 2}$$

$$M^* = M(k/k_0)^r \, (c_p/c_{p0})^s \qquad \text{Eq. 3}$$

$$E^* = E(k/k_0)^t \, (c_p/c_{p0})^u \qquad \text{Eq. 4}$$

Where the subscript "$_0$" refers to a reference gas such as methane and the m, n, p, q, r, s, t and u are exponents; and where S* equals the corrected value of the sensor signal S, V* equals the corrected value for the volumetric flow V, M* equals the corrected value for the mass flow, and E* equals the corrected value for the energy flow, E.

This technique of correcting the sensor signal, the mass flow, the volumetric flow and the energy flow is explained in greater detail in co-pending patent application serial no. 285,897, filed on December 16, 1988 and assigned to the common assignee of the present application.

It has been found that several groups of natural gas properties lend themselves to

advantageous determination of heating value for the gas. One of these groups is thermal conductivity and specific heat. The heating value, H, is determined by a correlation between the physical, measurable natural gas properties and the heating value.

Since thermal conductivity, k, and specific heat, $c_p$, have been determined for the fuel flowing through conduit 20, the heating value, H, of the fuel flowing through conduit 20 can be determined. By evaluating the polynomial

$$H = a_1 f_1^{n1}(x) \cdot A_2 f_2^{n2}(x) \cdot A_3 f_3^{n3}(x) \qquad \text{Eq. 5}$$

for a selection of over 60 natural gasses, the following were obtained:

$A_1 = 9933756$

$f_1(x) = k_c$ (thermal conductivity at a first temperature)

$n1 = -2.7401.$

$A_2 = 1,$

$f_2(x) = k_h$ (thermal conductivity at a second, higher temperature)

$n2 = 3.4684,$

$A_3 = 1,$

$f_3(x) = Cp$ (specific heat), and

$n3=1.66326$

The maximum error in the heating value calculation = 2.26 $btu/ft^3$ and the standard error for the heating value calculation = 0.654 $btu/ft^3$.

Alternatively, the heating value of the fluid in conduit 20 could be calculated by evaluating the polynomial of equation 5 using the following values:

$A_1 = 10017460,$

$f_1(x)$ = kc (the thermal conductivity at a first temperature),

n1 = -2.6793,

$A_2$ = 1,

$f_2(x)$ = $k_h$ (thermal conductivity at a second, higher temperature),

2n2 = 3.3887,

$A_3$ = 1,

$f_3(x)$ = $C_p$ (specific heat) and

n3 = 1.65151.

For these values, the maximum error in the calculation of heating value, H, equals 1.82 btu/ft$^3$ and the standard error equals 0.766 btu/ft$^3$.

It should be noted that, although equation 5 only uses thermal conductivity and specific heat to calculate the heating value, other fuel characteristics can be measured, such as specific gravity and optical absorption, and other techniques or polynomials can be used in evaluating the heating value of the fluid in conduit 20.

Having determined the volumetric or mass flow for the fluid in conduit 20 and for the air in conduit 17, and having determined the heating value of the fuel in conduit 20, energy flow (or btu flow) can be determined by the following equation.

$$E = H_v V = H_m M \qquad \text{Eq. 6}$$

where $H_v$ = the heating value in btu's per unit volume,

$H_m$ = heating value in btu per unit mass,

V = volumetric flow of the fuel, and

M = mass flow of the fuel.

By using the corrected value of the volumetric or mass flow (V* or M*) of the fuel in conduit 20,

the correct energy flow in btu/second flowing through conduit 20 can be determined.

Based on the energy flow through conduit 20 and the corrected mass or volumetric flow of air through conduit 17, the fuel flow or air flow can be adjusted to achieve a desired mixture.

A well known property of hydrocarbon-type fuels is that hydrocarbons combine with oxygen under a constant (hydrocarbon-independent) rate of heat release. The heat released by combustion is 100 btu/ft$^3$ of air at 760 mmHg and 20° C or (68° F). This is exactly true for fuel with an atomic hydrogen/carbon ratio of 2.8 and a heating value of 21300 btu/lb of combustibles and is true to within an error of less than +/- 0.20% for other hydrocarbons from methane to propane (i.e. $CH_4$, $C_2H_6$ and n-$C_3H_8$).

With this knowledge, combustion control can now be designed such that gaseous hydrocarbon fuels (the fuel through conduit 20) is provided to combustion chamber 12 in any desired proportions with air.

For example, in order to achieve stoichiometric (zero excess air) combustion, the mixture would be one cubic foot of air for each 100 btu of fuel (e.g. 0.1 cubic foot of $CH_4$). A more typical mix would be 10% to 30% excess air which would require 1.1 to 1.3 cubic feet of air for each 100 btu of fuel. This would be a typical mixture because residential appliances typically operate in the 40-100% excess air range while most commercial combustion units operate between 10 and 50% excess air.

Although the present invention has been described with reference to fuels with hydrocarbon

constituents, the fuel-to-air ratio in combustion heating system 10 can also be controlled when heating system 10 uses other fuels. Each fuel used in combustion requires or demands a certain amount of oxygen for complete and efficient combustion (i.e., little or no fuel or oxygen remaining after combustion). The amount of oxygen required by each fuel is called the oxygen demand value $D_f$ for that fuel. $D_f$ is defined as units of moles of $O_2$ needed by each mole of fuel for complete combustion. For example, the $O_2$ demand for $CH_4$, $C_2H_6$, $C_3H_8$, CO, $H_2$ and $N_2$ is $D_f$ = 2, 3.5, 5.0, 0.5, 0.5 and 0 respectively.

Air is used to supply the oxygen demand of the fuel during combustion. In other words, fuel is an oxygen consumer and air is an oxygen supplier or donator during combustion. The $O_2$ donation, $D_o$, is defined as the number of moles of $O_2$ provided by each mole of air. The single largest factor which influences $D_o$ is the humidity content of the air. Absolutely dry air has a value of $D_o = 0.209$, while normal room temperature air with 30% relative humidity (or 1% mole fraction of $H_2O$) has a value of $D_o = 0.207$.

With the addition of microbridge sensor 30 to heating system 10, various components of the air in conduit 17 can be sensed. For example, oxygen content, $D_o$, can be sensed and the presence of moisture (i.e., humidity) can be accounted for. By knowing these and other components of the air, (i.e., the composition of the air) in conduit 17, the fuel-to-air ratio in heating system 10 can be

controlled to acheive even more precise combustion control.

Therefore, combustion control can be accomplished by correlating the sensed k and $c_p$ of the fuel to the oxygen demand $D_f$ value rather than heating value of the fuel. Once the oxygen demand value of the fuel is known, the fuel-to-air ratio can be accurately controlled. By using the oxygen demand value of the fuel rather than the heating value, the fuel-to-air ratio of fuels with constituents other than hydrocarbons can be accurately controlled.

It should also be noted that, with the addition of microbridge sensor 30 in conduit 17, the corrected mass or volumetric flow for the air in conduit 17 can be determined in the same manner as the corrected mass or volumetric flow for the fuel is determined above. This further increases the accuracy of fuel-to-air ratio control.

## CONCLUSION

The present invention allows the fuel-to-air ratio in a heating system to be controlled based not only on the flow rates of the fuel and air but also on the composition of the fuel and air used in the heating system. Hence, the present invention provides the ability to reset the desired fuel and air flow rates so that a fuel-to-air ratio is achieved which maintains desirable combustion efficiency and cleanliness conditions (such as low level of undesirable flue gas constituents and emissions like soot, CO or unburned hydrocarbons).

Further, the present invention provides greater reliability and response time over systems where

sensors were exposed to flue gases. Also, the present invention provides compensation for changes in fuel and air composition while still providing a desirable feed-forward control.

In addition, this invention is well suited for use in a multi-burner composition chamber. If used, each burner would be individually adjustable.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

1. A method of controlling a fuel-to-air ratio in a heating system, comprising:

sensing fuel flow of fuel in the heating system;

sensing parameters representative of fuel composition of the fuel in the heating system;

determining fuel composition based on the sensed parameters;

determining energy flow in the heating system based on the fuel flow and the fuel composition;

sensing air flow of combustion air in the heating system; and

controlling the fuel-to-air ratio as a function of the energy flow determined and the air flow sensed.

2. The method of claim 1 wherein the step of determining fuel composition further comprises:

determining a heating value of the fuel.

3. The method of claim 2 wherein the step of determining a heating value further comprises:

sensing thermal conductivity of the fuel;

sensing specific heat of the fuel; and

determining the heating value of the fuel based on the thermal conductivity and the specific heat of the fuel.

4. The method of claim 1 wherein the step of sensing fuel flow further comprises:

sensing volumetric flow of the fuel;

determining correction factors for the volumetric flow; and

determining a corrected volumetric flow for the fuel based on the correction factors and the sensed volumetric flow.

5. The method of claim 1 wherein the step of sensing fuel flow further comprises:

sensing mass flow of the fuel;

determining correction factors for the mass flow; and

determining a corrected mass flow for the fuel based on the correction factors and the sensed mass flow.

6. The method of claim 1 wherein the step of sensing air flow further comprises:

sensing volumetric flow of the combustion air;

determining correction factors for the volumetric flow; and

determining a corrected volumetric flow for the air based on the correction factors and the sensed volumetric flow.

7. The method of claim 1 wherein the step of sensing air flow further comprises:

sensing mass flow of the combustion air;

determining correction factors for the mass flow; and

determining a corrected mass flow for the combustion air based on the correction factors and the sensed mass flow.

8. A method of controlling a fuel-to-air flow ratio in a heating system comprising:

setting a desired fuel-to-air flow ratio;

sensing fuel flow of fuel in the heating system;

sensing air flow of combustion air in the heating system;

sensing parameters representative of fuel composition of the fuel in the heating system;

determining fuel composition based on the sensed parameters;

determining energy flow in the heating system based on the fuel flow and the fuel composition; and

controlling the fuel-to-air flow ratio based on the energy flow determined and the air flow sensed.

9. The method of claim 8 wherein the step of determining fuel composition further comprises:

determining a heating value for the fuel.

10. The method of claim 9 wherein the step of determining a heating value further comprises;

sensing thermal conductivity of the fuel;

sensing specific heat of the fuel; and

determining the heating value of the fuel based on the thermal conductivity and the specific heat of the fuel.

11. The method of claim 8 wherein the step of setting a desired fuel-to-air flow ratio further comprises:

setting a fuel flow rate in the heating system; and

setting an air flow rate in the heating system.

12. The method of claim 11 wherein the step of controlling the desired fuel-to-air flow ratio further comprises:

resetting the fuel flow rate based on the energy flow determined.

13. The method of claim 11 wherein the step of controlling the desired fuel-to-air flow ratio further comprises:

resetting the air flow rate based on the energy flow determined.

14. The method of claim 11 wherein the step of setting a fuel flow rate further comprises:

setting a volumetric flow rate of the fuel.

15. The method of claim 11 wherein the step of setting a fuel flow rate further comprises:

setting a mass flow rate of the fuel.

16. The method of claim 14 wherein the step of setting an air flow rate further comprises:

setting a volumetric flow rate of the combustion air.

17. The method of claim 15 wherein the step of setting an air flow rate further comprises:

setting a mass flow rate of the combustion air.

18. An apparatus for controlling a fuel-to-air ratio in a heating system, comprising:

flow sensing means for sensing fuel flow of fuel in the heating system;

composition sensing means for sensing parameters representative of fuel composition of the fuel in the heating system;

composition determining means for determining fuel composition based on the sensed parameters;

flow determining means for determining energy flow in the heating system based on the fuel flow and the fuel composition;

air flow sensing means for sensing air flow of combustion air in the heating system; and

controlling means for controlling the fuel-to-air ratio as a function of the energy flow determined and the air flow sensed.

19. The apparatus of claim 18 wherein the composition determining means further comprises:

heating value determining means for determining a heating value of fuel based on the sensed parameters.

20. The apparatus of claim 19 wherein the heating value determining means further comprises:

thermal conductivity sensing means for sensing thermal conductivity of the fuel;

specific heat sensing means for sensing specific heat of the fuel; and

value determining means for determining the heating value of the fuel based on the thermal conductivity and the specific heat of the fuel.

21. The apparatus of claim 18 wherein the fuel flow sensing means further comprises:

volumetric sensing means for sensing volumetric flow of the fuel

correction means for determining correction factors for the volumetric flow; and

flow correction means for determining a corrected volumetric flow for the fuel based on the correction factors and the sensed volumetric flow.

22. The apparatus of claim 18 wherein the fuel flow sensing means further comprises:

mass flow sensing means for sensing the mass flow of the fuel;

correction means for determining correction factors for the mass flow; and

mass flow correction means for determining a corrected mass flow for the fuel based on the correction factors and the sensed mass flow.

23. The apparatus of claim 18 wherein the air flow sensing means further comprises:

volumetric flow sensing means for sensing volumetric flow of the combustion air;

correction means for determining correction factors for the volumetric flow; and

volumetric flow correction means for determining a corrected volumetric flow for the air based on the correction factors and the sensed volumetric flow.

24. The apparatus of claim 18 wherein the air flow sensing means further comprises:

mass flow sensing means for sensing mass flow of the combustion air;

correction means for determining correction factors for the mass flow; and

mass flow correction means for determining a corrected mass flow for the combustion air based on the correction factors and the sensed mass flow.

25. A method of controlling a fuel-to-air ratio in a heating system, comprising:

sensing fuel flow of fuel in the heating system;

sensing parameters representative of an oxygen demand value of the fuel in the heating system;

determining the oxygen demand value based on the sensed parameters;

sensing air flow of combustion air in the heating sytem; and

controlling the fuel-to-air ratio as a function of the fuel flow, the oxygen demand value of fuel and the air flow sensed.

26. The method of claim 25 wherein the step of sensing parameters representative of the oxygen demand value of the fuel further comprises:
sensing thermal conductivity of the fuel; and
sensing specific heat of the fuel.

27. The method of claim 26 wherein the step of determining the oxygen demand value further comprises:
determining the oxygen demand value of the fuel based on the thermal conductivity in the specific heat of the fuel.

28. The method of claim 25 and further comprising:
sensing air composition of the air in the heating system.

29. The method of claim 28 wherein the step of sensing air composition comprises:
sensing oxygen content of the air in the heating system; and
sensing moisture content of the air in the heating sytem.

30. The method of claim 25 wherein the step of sensing fuel flow comprises:
sensing volumetric flow of the fuel;
determining correction factors for the volumetric flow; and

determining a corrected volumetric flow for the fuel based on the correction factors and the sensed volumetric flow.

31. The method of claim 25 wherein the step of sensing fuel flow comprises:

sensing mass flow of the fuel;

determining correction factors for the mass flow; and

determining a corrected mass flow for the fuel based on the correction factors and the sensed mass flow.

32. The method of claim 25 wherein the step of sensing air flow comprises:

sensing volumetric flow of the combustion air;

determining correction factors for the volumetric flow; and

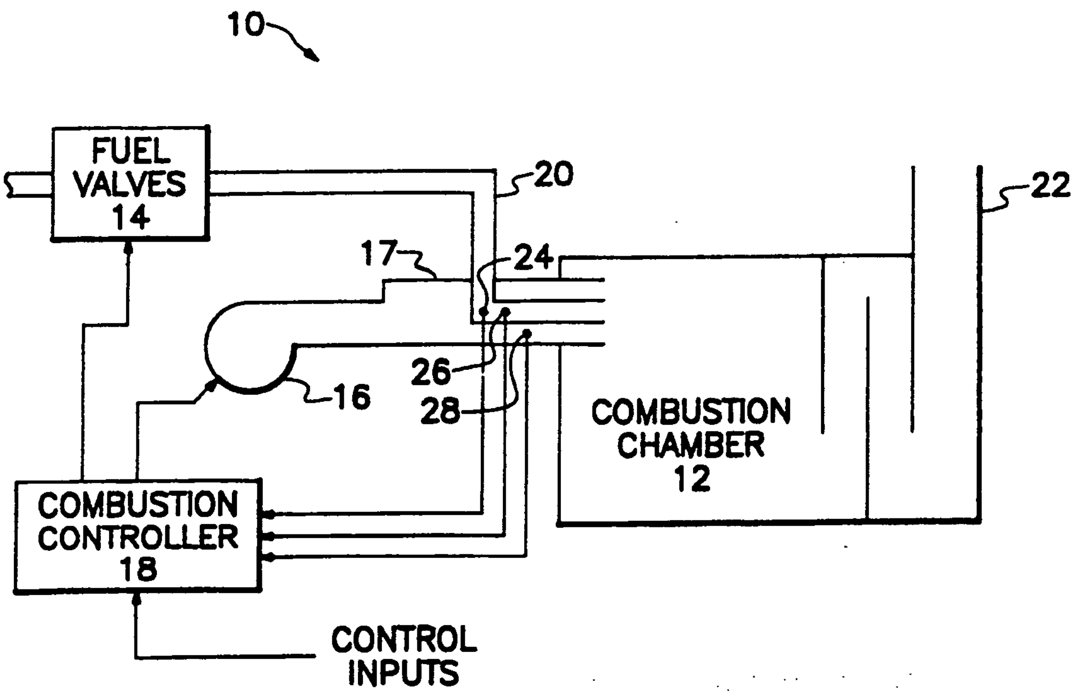
determining a corrected volumetric flow for the air based on the correction factors and the sensed volumetric flow.

33. The method of claim 25 wherein the step of sensing air flow comprises:

sensing mass flow of the combustion air;

determining correction factors for the mass flow: and

determining a corrected mass flow for the combustion air based on the correction factors and the sensed mass flow.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COMBUSTION
CHAMBER
12
COMBUSTION
CONTROLLER
18
CONTROL
INPUTS

# INTERNATIONAL SEARCH REPORT

International Application No PCT/US 90/05692

**I. CLASSIFICATION OF SUBJECT MATTER** (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 F23N5/18 ; F23N1/02

**II. FIELDS SEARCHED**

Minimum Documentation Searched[7]

| Classification System | Classification Symbols |
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| Int.Cl. 5 | F23N |

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

**III. DOCUMENTS CONSIDERED TO BE RELEVANT**[9]

| Category ° | Citation of Document, [11] with indication, where appropriate, of the relevant passages [12] | Relevant to Claim No.[13] |
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| A | DE,A,2745459 (MEASURING CORP.) 15 June 1978<br>see pages 11 - 15; figures | 1, 8, 18, 25 |
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**IV. CERTIFICATION**

| Date of the Actual Completion of the International Search | Date of Mailing of this International Search Report |
|---|---|
| 04 JANUARY 1991 | 12.02.91 |
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| III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET) | | |
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## ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. PCT/US 90/05692

SA 40858

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on
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